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Magnetic nanostructures Patterned by Self-Organized Materials

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14. ABSTRACT

In the period of this grant we have been working on several topics such as the classical and quantum theory of spin waves of magnets at the nanoscale; novel magnetic materials and interfaces; domain wall dynamics; and inter-element interactions. There are fundamental questions in these topics that we addressed, such as the effects of geometry and roughness on the reflection and transmission of spin waves on waveguides; mechanisms for controlling the anisotropy of nanometric samples; and the preparation of nano-elements with interesting and promising magnetic and transport properties by combining different techniques such as chemical synthesis, self-organized methods, sputtering, lithography and atomic layer deposition (ALD). In thin films, we have been working on the control of magnetic anisotropy in magnetic multilayers in order to obtain spin valves and enhance the magnetoresistance and Hall Effect. We also started to perform e-bean lithography in order to reduce the dimensions of the nanoelements, and then improve the performance of the systems aiming to possible sensor devices.

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FINAL REPORT
October 1, 2013-September 30, 2015

MAGNETIC NANOSTRUCTURES PATTERNED BY SELF-ORGANIZED MATERIALS
AFOSR – AFOSR FA9550-11-1-0347

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1. OBJECTIVES

The underlying idea on this research project is to introduce structural modifications at the micro and nano scales in order to generate periodic or regular modifications in the shape of magnetic materials that will result in the accumulation of surface magnetic charges. The dipolar interaction associated to such a distribution will traduce itself in a shape anisotropy. As stated previously, the control over the magnetic anisotropy will lead to a control of magnetoresisitve and even electromagnetic properties of materials.

2. ANNUAL ACCOMPLISHMENTS

In the period of this grant we have been working on several topics such as the classical and quantum theory of spin waves of magnets at the nanoscale; novel magnetic materials and interfaces; domain wall dynamics; and inter-element interactions. There are fundamental questions in these topics that we addressed, such as the effects of geometry and roughness on the reflection and transmission of spin waves on waveguides; mechanisms for controlling the anisotropy of nanometric samples; and the preparation of nano-elements with interesting and promising magnetic and transport properties by combining different techniques such as chemical synthesis, self-organized methods, sputtering, lithography and atomic layer deposition (ALD). We also performed micromagnetic and Monte-Carlo simulations, using commercial codes and our own codes. In thin films, we have been working on the control of magnetic anisotropy in magnetic multilayers in order to obtain spin valves and enhance the magnetoresistance and Hall Effect. Magnetic multilayers and spin valves with perpendicular anisotropy can have promising applications as magnetic sensors, and one of the methods we are using to enhance the out-of-plane anisotropy is the deposition of the films on modulated substrates. We also started to perform e-beam lithography in order to reduce the dimensions of the nanoelements, and then improve the performance of the systems aiming to possible sensor devices.

Our group has supported the implementation of several new techniques of fabrication and characterization of magnetic nanostructures that position our group in a very good level, and with the advantage that we also have a very competitive group of theoretical researchers working very close to the laboratory. It is important to mention that this laboratory is the only one in our country in which it is possible to measure magnetic properties of particles at low temperatures and high fields. With the cryogen free VSM (Cryogenic LTD) that was installed in December of 2012, we undertake the characterization of magnetic materials in a wide range of temperatures (1.8 to 300 K) and at high fields (up to 5 T). The low temperature measurements of magnetic nanoparticles allowed us to determine the blocking temperature of superparamagnetic systems, and to evaluate the applicability of these systems in drug delivery.
Structural characterizations have been possible since we acquired a SEM microscope in 2010. This microscope allows precise morphological analyses of the nano-elements synthesized by our group and provides services to other research groups. In 2014 we installed an EDS microanalysis system to the SEM microscope and we also installed an e-beam pattern generator for the SEM (NPGS), in order to make nanolithography. With e-beam lithography we will be able to pattern different nanostructures and characterize their electrical and magnetic properties.

A. Self organized arrays of antidots.

We have investigated the magnetic properties of permalloy [**Journal of Magnetism and Magnetic Materials 350,** 88-93 (2014)] and cobalt [**Journal of Physics D: Applied Physics 47**, 335001 (2014)] magnetic antidot arrays with different hole sizes. Importantly, these articles considered the synthesis of antidots, morphological and magnetic characterization, and theoretical study by micromagnetic simulations. Indeed, in order to investigate the influence of the natural disorder of the net of holes, and the imperfections of the circularity of each hole, we have utilized three-dimensional modeling using the SEM image as a bitmap. The process consists of transforming a SEM image in a black and white image, which can be read for the OOMMF package.

In a paper published in **Journal of Physics D: Applied Physics 47, 335001 (2014)**, the magnetic properties of Co antidot arrays with different hole sizes fabricated by a template-assisted method have been studied by means of first-order reversal curves (FORCs) and micromagnetic simulations. Hysteresis curves show a significant increase of the coercivity of the antidot arrays, as compared with their parent continuous film, which depends on the hole size introduced in the Co thin film. This effect is related to the reversibility of the magnetic domains during magnetization reversal, since due to the appearance of pores, domains may become trapped between them. On the other hand, micromagnetic simulations reveal that the presence of defects in the antidot lattice affects its magnetic properties.

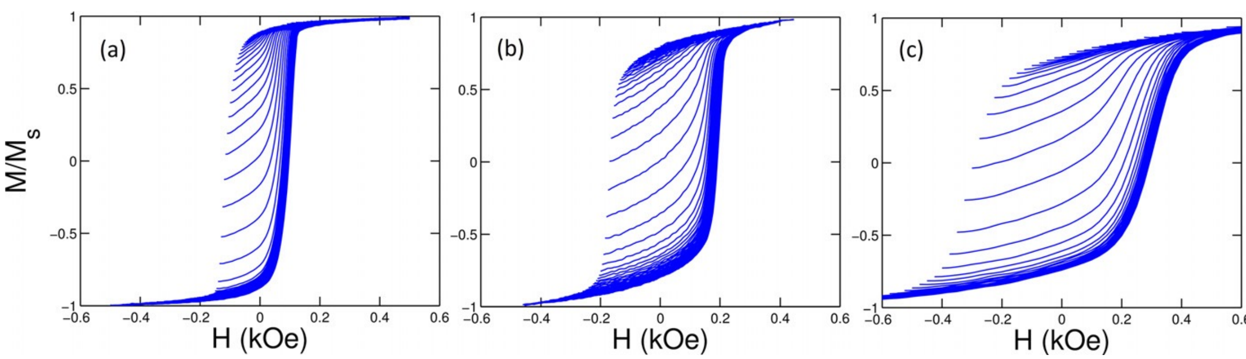

Figure 1. FORCs for antidot arrays with a pore diameter of (*a*) 20 nm, (*b*) 40 nm and (*c*) 60 nm, when the external field is applied parallel to the plane of the antidots.

B. Magnetization reversal in special geometrical nanoelements.

A detailed numerical analysis of the magnetization reversal processes in T-shaped nanoparticles has been carried out and the results are published in **Applied Physics Letters 104,** 123102 (2014). Attention has been focused on the influence of the symmetry of the particle on the formation, propagation, and interaction of internal magnetic structures such as domain walls, vortices, and antivortices. Results show that the lower the degree of symmetry of the particle, the more complex the reversal process is. Thus, symmetry represents an additional ingredient to control the magnetic properties of ferromagnetic nanoparticles.

The magnetization reversal mechanisms of small rings have been investigated as a function of the geometry [**Journal of Applied Physics 115**, 223903 (2014)]. Stepped and nonstepped hysteresis loops were obtained and four different reversal mechanisms were identified. In spite the important information that is possible to get from the hysteresis loops, in some cases it is not possible to identify from them the reversal mechanisms. However, susceptibility curves deliver enough information to determine precisely the reversal mode, making these curves a valuable tool for the study of the magnetization

By means of Monte Carlo simulations we explore the reversal modes of rings with diameters smaller than 100 nm, dimensions that have not been systematically explored. In this regime, four reversal modes were obtained as a function of the geometry. These modes can be grouped in two categories. Two of them involve vortex formation (DWV and LV), and two does not generate vortices (DW and T). Also they can be classified according to whether they consider or not domain wall propagation. Again, two modes involve domain wall propagation (DWV and DW) and two do not include it (LV and T). These modes appear for different geometries. While thick rings prefer no wall formation modes, thin small rings prefer wall formation. Rings of medium thickness present all four reversal modes as a function of q. Some of these modes are not clearly distinguishable from the hysteresis loops, but their differences appear clearly in the susceptibility, making these curves serve as a tool that allows a clear identification of the reversal processes involved.

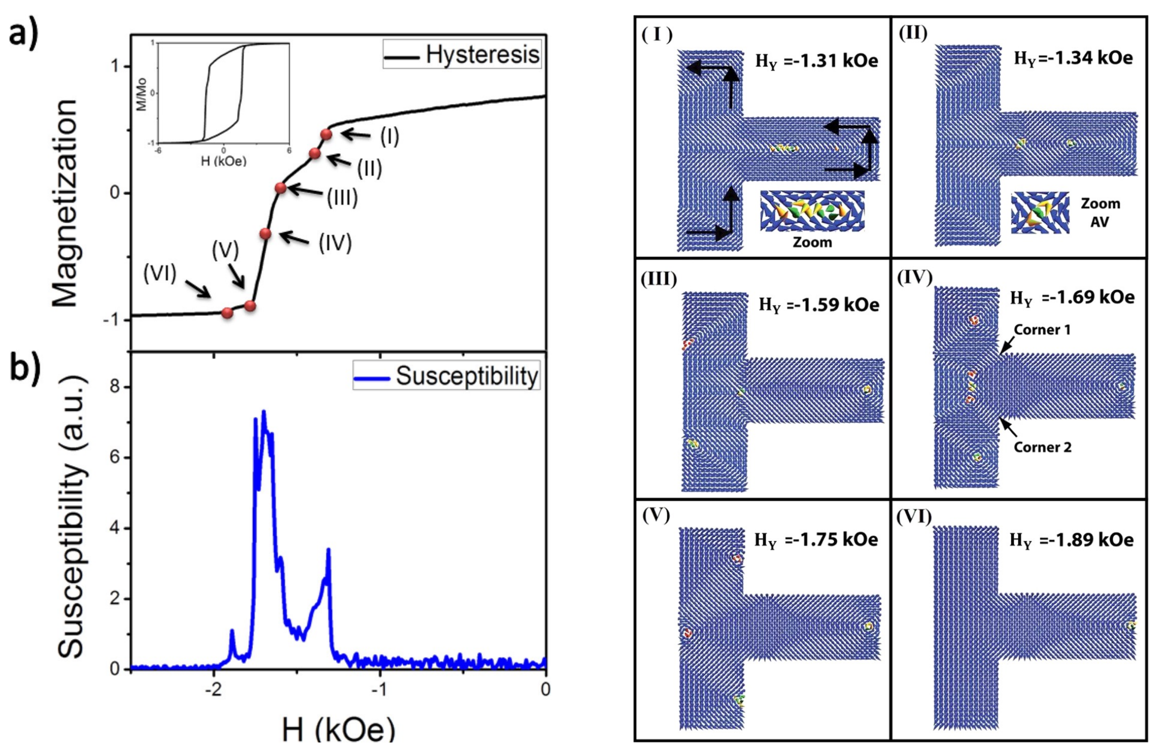

Figure 2. (left) Magnetization and susceptibility curves in the neighborhood of the coercivity, for the external field applied along the y axis. The inset in Figure 2(a) shows the entire hysteresis curve. Points on the magnetization curve indicate the passage of the system through states in which the magnetization varies very rapidly. (right) Snapshots of the configuration of the magnetic moments at those stated indicated by dots in left Figure 2.The arrows denote two 90 and one 180 walls.

It is important to mention that we can now fabricate these nanoelements by e-beam lithography and then observe experimentally the vortex states using MFM.

Student graduation:

During 2015 the student Nicolás Vargas finished his PhD, and was working on the thesis under supervision of Dr. Denardin and Dr. Dora Altbir. He was working on the development of waveguides by lithography for the study of high frequency magnetic properties of arrays of nanowires. During this year the student Roberto Escobar also finished his PhD thesis under the supervision of Dr. Dora Altbir. His work is presented in topic B above.

3. ARCHIVAL PUBLICATIONS

1. R. Lavín, C. Farías, J. C. Denardin *FORC analysis of Ni(SiO2) nanogranular film in the blocked regime* **Journal of Magnetism and Magnetic Materials 324** 1800-1803 (2012).

2. B. Leighton, A. Pereira, J. Escrig *Reversal modes in asymmetric Ni nanowires* **Journal of Magnetism and Magnetic Materials 324,** 3829-3833 (2012).

3. R. M. Corona, D. Altbir, J. Escrig *Magnetic properties of elliptical and stadium-shaped nanoparticles: Effect of the shape anisotropy* **Journal of Magnetism and Magnetic Materials 324,** 3824-3828 (2012).

4. R. Lavín, C. Gallardo, J. L. Palma, J. Escrig, J. C. Denardin *Angular dependence of the coercivity and remanence of ordered arrays of Co nanowires* **Journal of Magnetism and Magnetic Materials 324,** 2360-2362 (2012).

5. Briones, J.; Toro, P.; Encinas, A.; Caballero, L.; Denardin, J. C.; Melo, F.; Cerda, E.; Robert, S.; Lacour, D.; Montaigne, F., Large area patterned magnetic films by depositing cobalt layers on nano-wrinkled polydimethylsiloxane templates, **APPLIED PHYSICS LETTERS** Volume: 103 Issue: 7 Article Number: 072404 DOI: 10.1063/1.4818677 Published: AUG 12 2013.

6. J. L. Palma, C. Gallardo, L. Spinu, J. M. Vargas, L. S. Dorneles, J. C. Denardin, J. Escrig, Magnetic properties of Fe20 Ni80 antidots: Pore size and array disorder, **Journal of Magnetism and Magnetic Materials**., 344, 2013, 8-13

7. E. Vargas, P. Toro, J.L. Palma, J. Escrig, C. Chaneac, T. Coradin, J.C. Denardin, *Facile synthesis and magnetic characterizations of single-crystalline hexagonal cobalt nanoplates*, **Materials Letters**, 94, 2013, 121-123

8. Pereira, A.; Gallardo, C.; Espejo, A.P.; Briones, J.; Vivas, L.G.; Vazquez, M.; Denardin, J.C.; Escrig, J., Tailoring the magnetic properties of ordered 50-nm-

diameter CoNi nanowire arrays, **JOURNAL OF NANOPARTICLE RESEARCH,** Volume: 15 Issue: 11, DOI: 10.1007/s11051- 013-2041-3, OCT 17 2013.

9. R. L. Rodríguez-Suárez, J. L. Palma, E. O. Burgos, S. Michea, J. Escrig, J. C. Denardin, C. Aliaga *Ferromagnetic resonance investigation in permalloy magnetic antidot arrays on alumina nanoporous membranes* Journal of Magnetism and Magnetic Materials 350,88-93 (2014)
10. R. A. Escobar, N. M. Vargas, S. Castillo-Sepúlveda, S. Allende, D. Altbir and J. d'Albuquerque e Castro *Complex magnetic reversal modes in low-symmetry nanoparticles* Applied Physics Letters 104, 123102 (2014)
11. E. Vargas, J. C. Denardin, R. Lavín, P. Mascaro, C. Chaneac, and T. Coradin*Magnetization analysis of oriented chains of hexagonal cobalt nanoplates* Journal of Applied Physics 115, 17B521 (2014)
12. S. Castillo-Sepúlveda, N. M. Vargas, R. Escobar, S. Allende, S. Baltazar and D. Altbir*Reversal modes in small rings: Signature on the susceptibility* Journal of Applied Physics 115, 223903 (2014)
13. S. Michea, J. L. Palma, R. Lavín, J. Briones, J. Escrig, J. C. Denardin and R. L. Rodríguez-Suárez *Tailoring the magnetic properties of cobalt antidot arrays by varying the pore size and degree of disorder* J. Phys. D: Appl. Phys. 47, 335001 (2014)
14. R. M. Freire, P. G. C. Freitas, T. S. Ribeiro, I. F. Vasconcelos, J. C. Denardin, G. Mele, L. Carbone, S. E. Mazzetto, P. B. A. Fechine *Effect of solvent composition on the structural and magnetic properties of MnZn ferrite nanoparticles obtained by hydrothermal synthesis* Microfluid Nanofluid 17, 233-244 (2014).
15. Ever Alberto Vel´asquez, Johan Mazo-Zuluaga, Dora Altbir, and Jose Mejıa-Lopez, *Ornstein-Zernike correlations and magnetic ordering in nanostructures*, Eur. Phys. J. B 87: 61 (2014).
16. E. Vargas, W.W.M. Melo, **S. Allende**, R.F. Neumann, **J.C. Denardin**, **D. Altbir**, M. Bahiana **Dipolar-driven formation of cobalt nanoparticle chains in polyethylene films** Materials Chemistry and Physics 162, 229-233
17. V. L. Carvalho-Santos, P. R. G. Elias, J. M. Fonseca, **D. Altbir Curvature-induced changes in the magnetic energy of vortices and skyrmions in paraboloidal nanoparticles** Journal of Applied Physics, 117, 17E518
18. P. S.C. Vilas-Boas, R. G. Elias, **D. Altbir**, J. M. Fonseca, V. L. Carvalho-Santos **Topological magnetic solitons on a paraboloidal shell** Physics Letters A Vol. 379 (1-2), 47-53
19. S. K. Sharma, J. M. Vargas, N. M. Vargas, S. Castillo-Sepúlveda, **D. Altbir**, K. R. Pirota, R. Zboril, G. Zoppellaro, and M. Knobel **Unusual magnetic damping effect in silver-cobalt ferrite hetero nano-system** RSC Advances 5, 17117-17122
20. **V.C.Santos**, G.Elias, J.Fonseca, **D.Altbir Stability of skyrmions on curved surfaces in the presence of a magnetic field** Journal of Magnetism and Magnetic Materials 391, 179–183

4. Changes in research objectives, if any: None

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